Investigation of Orthogonal Turn-Milling for the Machining of Rotationally Symmetrical Workpieces

A Thesis submitted
in Partial Fulfillment of the Requirements
for the Degree of
MASTER OF TECHNOLOGY

by

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to the

Department of Mechanical Engineering
INDIAN INSTITUTE OF TECHNOLOGY, KANPUR

January, 1999

Dedicated
To
My parents

Certificate

It is certified that the work contained in the thesis entitled " **Investigation of Orthogonal Turn-Milling for the machining of Rotationally Symmetrical Workpieces** ", by **Mangrulkar Kaustubh Subhash** has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

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January, 1999

Acknowledgement

I take this opportunity to express the feeling of sincere gratitude towards my thesis supervisor Dr S K Choudhury for his expert guidance and encouragement which have been the vital factors in successful completion of the present work. I wish to express my gratitude towards Prof Dr -Ing H Schulz, Technical University of Darmstadt, Germany, for his invaluable cooperation in providing me the literature which otherwise could not have been available for this research work

I would like to thank Shri R M Jha of the Manufacturing Sci. Lab. and Shri B P. Vishvakarma of the Central Workshop for their guidance and help in all the technical matters without which this work could not have been brought into reality. A word of thanks also goes to Shri Namdev Murkhe and Shri H. P Sharma of the Manufacturing Sci. Lab and all the staff of the Central Workshop for their assistance during fabrication of the Turn-Milling attachment and during the actual experimental work.

It is indeed my great pleasure to express my sincere thanks to Ashok Umranikar, Subodh Kulkarni, Amol Bhangale, Amit Kumthekar and all my friends for their timely help and friendly cooperation in sorting out my problems and making my stay at I.I.T., Kanpur, a pleasant and memorable one. I am very much grateful to my parents who always supported me despite many problems in all the circumstances. I have a special word of thanks for my beloved sister Shraddha who never made me feel lonely by her calls and letters during my days at I.I.T , Kanpur.

Mangrulkar Kaustubh S.

Abstract

Conventional manufacturing processes like turning or milling approach their limits with regard to technology and economy In turning operations, high cutting speeds are limited due to the centrifugal stresses of the clamping chuck. To overcome these limitations, the rotation of the tool can be combined with the rotary motion of the workpiece. ' Turn-Milling ' is a relatively new concept in manufacturing technology, wherein both the workpiece and the tool are given a rotary movement simultaneously. This new technology opens up new ranges of applications in the manufacturing processes. Turn-Milling can be classified into co-axial turn-milling in which the axes of the cutter and the workpiece are parallel and orthogonal turn-milling in which the axes are perpendicular

The objective of the present work is to investigate the process of orthogonal turn-milling for the machining of rotationally symmetrical workpieces within the normally available range of speeds and feeds (comparable to those used in turning) with easily available tool materials to explore its advantages The emphasis has been laid mainly on the surface finish of the machined surface achieved. The experimental set-up required fabrication of the attachment for orthogonal turn-milling to be carried out on a vertical milling machine. The experiments have been conducted for orthogonal turn-milling of brass and mild-steel workpieces to study the surface finish achieved. The experiments have been planned according to the design of experiments to reduce the number of experiments and to obtain the regression equations to evaluate the surface roughness of the machined surface for both the workpiece materials. The experiments on turning have been conducted for both the workpiece materials to make a comparative study of the surface finish and the chip geometry achieved in case of orthogonal turn-milling and turning processes.

The experimental results show that in orthogonal turn-milling, the surface finish of the machined surface improves with increase in cutter speed and deteriorates with increase in axial feed rate. The surface finish achieved by orthogonal turn-milling is about 10 times higher than that achieved by turning. Also, the chips produced in orthogonal turn-milling are very small as compared to the chips produced in turning. Hence, orthogonal turn-milling can be an alternative to turning where high surface finish and easy chip disposal are desired.

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Nomenclature

R_a, R_z = surface roughness values (μm)

r_1, r_2 = rotation radii of the cutting edges (mm)

$\phi 1$, $\phi 2$ = angles for an instantaneous relative position of the cutting edge and the workpiece (rad)

ω = angular velocity (rad/min)

v_f = feed rate (mm/min)
d_T = tool diameter (mm)

d_w = workpiece diameter (mm)

l_{ax} = Length of the workpiece (mm)

l_f = feed equivalent to the length of the spiral path curve (mm)

a_p = Lead of the spiral path (mm)

e = eccentricity of the tool-axis from the workpiece-axis (mm)

x_1, x_2 = variables in the regression equation representing cutter speed and axial feed rate

y = output response quantity in the regression equation representing R_a-value of the surface roughness

N_T = rotational speed of the cutter (RPM)

N_w = rotational speed of the workpiece (RPM)

f = axial feed rate (mm/min)

z = number of teeth on the milling cutter

f_e = equivalent feed rate (mm/rev)

Chapter 1

Introduction

Material removal is one of the oldest and major manufacturing processes for the economic production of elaborately transformed manufactures. In this process, the component geometry is generated by systematically removing the excess material from a workpiece by means of a cutting tool which interferes with, and moves relative to the workpiece in a predetermined and controlled manner. Numerous ingenious, and geometrically complex practical machining operations such as turning, milling and shaping have been developed to generate a wide spectrum of component shapes and sizes.

Conventional manufacturing processes, e.g. turning or milling, often approach their limits with regard to technology and economy. In turning operations, high cutting speeds are limited due to the centrifugal stress of the clamping chuck. In milling, the limitation is due to the centrifugal forces acting upon the tool. These limitations can be overcome if the rotation of the workpiece can be combined with the motion of a rotating tool.

The 'Turn-Milling' is a relatively new concept in manufacturing technology, wherein both, the workpiece and the tool, are given a rotary movement simultaneously. This new technology opens up new ranges of applications in the manufacturing processes. In high precision cutting, surface qualities down to $R_z = 1\ \mu$ as well as dimensional and shape tolerances of 'IT4' are often required. Normally, these goals can only be achieved by grinding. Recently, efforts have been made to substitute the grinding process with all its problematic strains by methods with geometrically defined cutting edges. It has been observed that high speed turn-milling is suitable for the precision machining of rotationally

symmetrical workpieces. Hence, when rotationally symmetrical workpieces are to be manufactured, high speed turn-milling can be an alternative to grinding.

With high speed turn-milling, high cutting speeds can be achieved by utilizing the two cutting speeds of the tool and the workpiece. Therefore, the advantages of high speed machining, e g. high surface quality, low thermal stress of the cutting edge, low cutting forces can be achieved In addition, good chip removal can be achieved due to their short length. This results in improved possibilities for automation of the process Hence, Turn-Milling' is a new prospective technology for the production of precise rotationally symmetrical workpieces.

1.1 Literature Review

Here a brief review is presented of the pioneer works in the field of turn-milling. some research papers related to self-propelled and driven rotary tool cutting processes have also been discussed since this can be regarded as the preliminary work towards the development of the innovative technology of turn-milling.

Shaw, et. al.[1], have discussed a novel lathe-type cutting tool in the form of a disc that may be rotated about its central axis. Such a rotary tool is found to correspond to an equivalent oblique tool. The rotary tool used by the authors has the following advantages :

1. It provides a rest period for the cutting edge, thus enabling the edge to be cooled and the adsorbed film on the tool surface to be replenished between cuts,

2 It enables the relative chip velocity to be increased to provide a lower coefficient of friction without necessitating a corresponding increase in the metal removal rate.

The authors have shown that a rotary tool of 10° rake angle is capable of reducing total power required to make a given cut by 30% and at the same time to operate with a temperature about 400 °F lower than that for the equivalent stationary tool.

In case of a rotary tool, a particular portion of the cutting edge is in operation for a very brief period, which is followed by a much longer rest period during which the thermal energy associated with cutting has ample opportunity to be dissipated to the bulk of the cutter. In this respect, the rotary tool resembles a multi-toothed tool such as a milling cutter. Such rotary tools have been used in both, positively driven and self-propelled types. Figure 1.1 shows a rotary tool being used for a rough-turning operation

According to Venuvinod, et. al. [2], the rotary tool takes the form of a frustum of a cone. The experiments conducted by them showed that with a proper selection of rotary

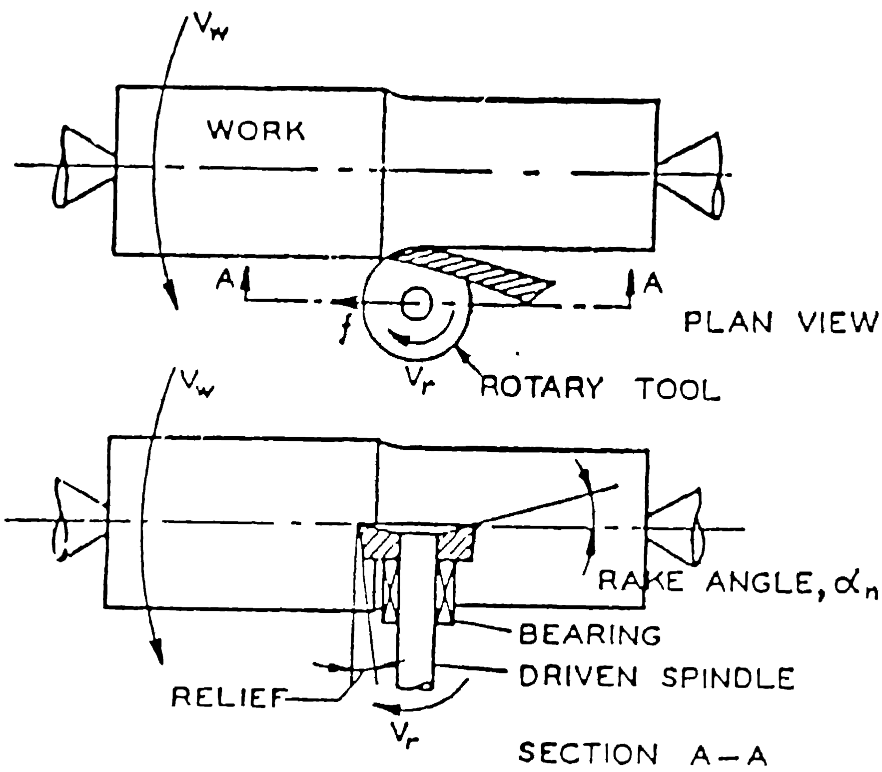


Fig. 1.1 : Rotary tool shown in use in rough turning operation

speeds, extraordinary effects on the cutting process are observed, e.g. reduction of cutting forces down to 10% and chip thickness ratios lesser than unity. Three distinct causes for the improvement of the cutting process are.

1. the effect of rotary speed, in the moderate speed range, on the kinematics of chip formation,
2. easing of the friction conditions at the chip-tool interface at very high speed ratios,
3. reduced thermal effects at chip-tool interface at very high speed ratios.

It is seen that if reduction in temperature and improvement in tool life are desired, 'self propelled rotary tool' (SPRT) is a possible solution. If reduction in cutting forces is desired, the 'driven rotary tool' (DRT) may be used.

Ping CHEN [3] reported that cutting temperature and cutting forces are the two dominant parameters that influence finish quality and tool life in machining. According to studies conducted by him on the self-propelled rotary tool, it has been observed that the rotary motion of the cutting edge transfers heat away from the cutting zone resulting in a reduced cutting temperature. Cutting forces of the rotary tool are also found to be smaller than those of the fixed tool. Consequently, reduced cutting temperature and decreased cutting forces are found to be the features of the rotary tool.

Armarego, et al. [4], conducted studies on the driven and the self-propelled rotary tool cutting operations and their relationships to the kinematically and perfectly equivalent 'classical' orthogonal and oblique cutting processes were explored. The self-propelled oblique rotary tool cutting process was modeled as a perfectly equivalent classical orthogonal cutting process together with chip transportation. It has been shown that the driven oblique rotary tool cutting process is the most efficient rotary tool process.

Konig, et. al. [5], worked on the means of reducing production time and costs for machining hard materials Highly stressed steel components are frequently hardened to increase their strength and wear resistance. Where there are high demands on workpiece quality, i.e on surface finish and accuracy-to-shape-and-size, the part has to be finished in a highly tempered or hardened state. Hitherto, a grinding process has generally been used to finish materials with hardness values in excess of 60 HRC, but improved knowledge of process and the consistent exploitation of modern cutting materials now enable cutting processes with a geometrically defined edge to be employed. A variety of machining tasks

can be performed with improved surface quality and high accuracy-to-size dispensing with the need for finish grinding. Higher machining rates as compared to grinding often result in a reduction in production times and costs.

Konig, et al., [6] had conducted studies in the technology of machining hardened steels with geometrically defined cutting edges Despite its high potential to increase the productivity as well as competitiveness, the industrial use is still low because the effects of hard machining on surface integrity aspects and the attainable accuracies are not well understood. With the development of modern superhard cutting materials with geometrically cutting edges, an alternative to grinding has been emerged. Substantial advantages achieved by the use of this innovative technology are in terms of more flexible, lower cost, more environment friendly production as compared with the energy and cost intensive grinding process.

The pioneer work in the field of turn-milling has been carried out in Germany by Schulz, et al [7] The experiments have been conducted for the machining of roller bearing races using high speed turn-milling. The study was made for orthogonal as well as coaxial turn-milling with the emphasis on surface-finish, geometric accuracy and chip geometry. It will be discussed in more details while dealing with the theoretical aspects of turn-milling in the chapter (2).

Schulz and Kneisel [8], have studied turn-milling with parallel axes as an alternative to precision-machining of hard materials by turning, especially for the machining of workpieces where certain limitations for turning exist. It has been shown that the surface quality of the workpieces is comparable to achieved by grinding and improvement in tool-life has also been reported with optimized cutting conditions. Again, it will also be discussed into a greater depth in chapter (2).

1.2 Objective and Scope of the Present Work

Turn-milling for the production of rotationally similar workpieces is a relatively new technology in which not much research has been done. The studies conducted are mainly for high speed turn-milling (cutting velocities exceeding 20000 m/min) for the

precise machining utilizing modern tool materials. It was felt that the process should be experimentally studied at the normally available speeds and feeds using readily available cutting tools. The lack of substantial research work in this area was really the motivation behind undertaking this study.

The aim of the experimental work is to investigate the innovative process of 'turn-milling' in the generally available range of speeds and feeds with easily available cutting tools, so as to explore its advantages The emphasis is laid mainly on surface finish of the workpieces machined by turn-milling. The experiments are confined to the range of cutter-speeds from 500 RPM to 2000 RPM and the range of axial-feeds from 8 mm/min to 12.5 mm/min The surface finish achieved by turn-milling is compared with that achieved by turning using comparable parameters

1.3 Organization of the Thesis

The thesis has been divided into five chapters as :

1. In chapter 2, the theoretical aspects of the 'Orthogonal Turn-Milling ' and the 'Co-axial Turn-Milling ' are discussed to explain the concept of 'Turn-Milling '.

2. In chapter 3, the experimental procedure is described alongwith the brief description of the equipment required to conduct the experiments. The experiments were planned as per the standard design of experiments [9], to reduce the number of experiments and to improve the results.

3. In chapter 4, results and discussion of the experiments on ' Turn-Milling ' as well as ' Turning ' are presented. The comparative study is made of the surface-finish achieved in orthogonal turn-milling of brass and mild-steel workpieces. The surface-finish achieved in orthogonal turn-milling and in turning are compared for brass and mild-steel workpieces to show the advantages of the turn-milling.

4. Finally, in chapter 5, the general conclusions drawn after the analysis of the experimental work are presented. Some suggestions are given which could be helpful for carrying out research in the field of 'Turn-Milling'.

Chapter 2

Theoretical Aspects

Turn-milling may be defined as a milling process in which both, the workpiece and the tool are given a rotary movement [7]. As shown in the Fig. 2.1, turn-milling can be classified into

a. Co-axial turn-milling in which the axes of the cutter and the workpiece are parallel to each other;

b. Orthogonal turn-milling in which the axes of the cutter and the workpiece are perpendicular to each other.

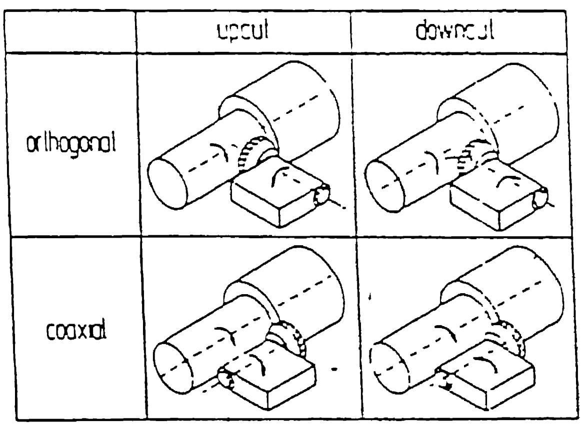


Fig. 2.1 : Arrangement of axes with high speed turn-milling

2.1 Co-Axial Turn-Milling

Co-axial turn-milling is suitable for internal as well as external machining of rotationally symmetrical workpieces.

2.1.1 Characteristics of Turn-Milling with Parallel Axes [8]

The combination of a fast rotating milling cutter and a slow rotating workpiece results in several advantages·

1. Short chips are produced due to process kinematics even in case of ductile materials.

2. Machining with optimized cutting speed is possible, both for large and unbalanced workpieces as well as for the workpieces with smaller diameters.

3. Contrary to turning, there are only small oscillation frequencies in the linear axes because
the rotational speed of the workpiece is relatively small.

4. Machining of hardened steel without any coolant is possible.

2.1.2 Influence of cutting edge configuration (Radial Deviation) on Surface Quality

Since the distance of the centre of the milling cutter from a point on the cutting edge varies, rotational speed varies along the length of the cutting edge. Therefore, irregularities in the structure of the machined surface occur. The exact, quantitative effect on the degeneration of surface quality can be described by the following set of non-linear equations. (Eqn. 2 1 & Eqn. 2 2). It can be numerically solved by means of the multidimensional Newtonian method. Figure 2 2 demonstrates this for a two-edged cutter.[8]

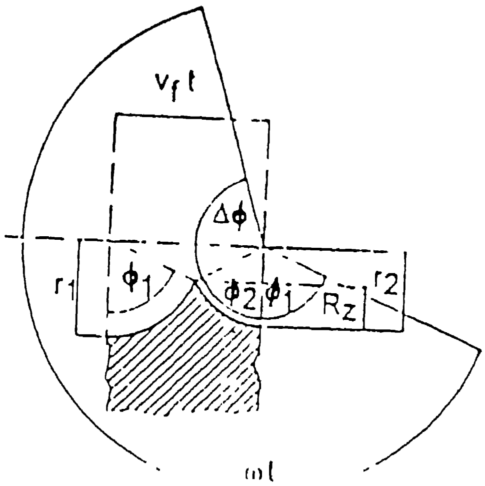


Fig. 2.2 : Formation of kinematic uneveness of a dual-edged cutter with radial deviation [8]

$$r_1 \cos\phi_1 - r_2 \cos\phi_2 = 0 \ldots\ldots \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(2.1)$$

$$\frac{f}{2\pi}(\phi_1 + \phi_2 + \Delta\phi) - r_1 \sin\phi_1 - r_2 \sin\phi_2 = 0 \ldots\ldots\ldots\ldots(2.2)$$

where,

r_1, r_2 = rotation radii of the cutting edges,

$\Delta\phi$ = angular pitch between edges 1 & 2 (rad.),

f = feed per revolution (mm/rev.),

ϕ_1, ϕ_2 = angles for an instantaneous relative position of the cutting edge and the workpiece (rad.)

ω = angular velocity (rad/min.),

v_f = feed rate (mm/min)

The surface unevenness, expressed as the average peak-to-valley height, R_z, can be calculated using the angle ϕ_1: [8]

$$R_z = \max(r_1, r_2) - r_1 \cos\phi_1 \quad (2.3)$$

Thus, a quantitative evaluation of the allowed radial deviation (r_1 and r_2) is possible. Even a slight eccentricity undermines an improvement of the surface quality normally obtained using multiple cutting edges. The cutting edge with the largest radius determines the surface quality and a milling cutter for high surface qualities has either only one cutting edge or has to be used at infeeds f similar to a single edged cutter.

2.1.3 Achievable feed Rates

The restrictions mentioned above concerning the number of cutting edges as well as the realizable infeeds result in reactions to the efficiency of the process. If the goal is to have a technologically optimized cutting speed as well as a pre-determined surface quality, infeed and rotational speed of the cutter have to be adjusted so that these values are maintained. As shown in Fig. 2.3, the infeed travel per tool rotation along the contour, i.e. the feed is dependent upon the diameter of the tool and the workpiece.

The feed f can be calculated by means of the angle ϕ: [8]

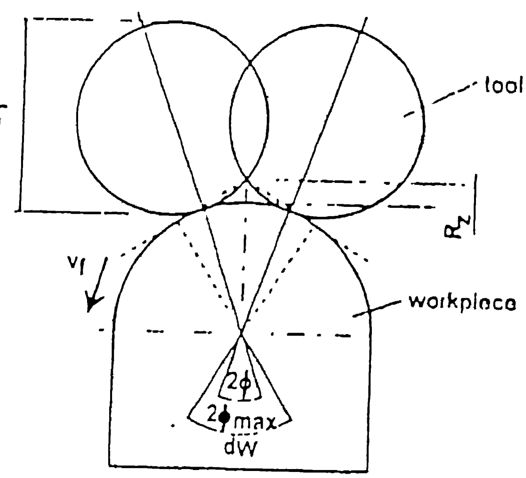


Fig. 2.3 : Meshing conditions during peripheral milling of curved workpiece contours

$$\cos\phi = \frac{-d_T^2+(d_W+2R_z)^2+(d_W+d_T)^2}{2(d_W+2R_z)(d_W+d_T)} \quad \text{.......................(2.4)}$$

$$f = \phi . d_W \quad \text{.......................(2.5)}$$

where,

d_W = workpiece diameter (mm),

d_T = tool diameter (mm)

Feed rate, v_f(mm/min), is calculated by implementing cutting speed, Vc.

$$v_f = \frac{\phi}{\pi}\frac{d_W}{d_T}v_C \quad \text{.......................(2.6)}$$

referring to Eqn. 2.6, V_f is expected to be inversely proportional to the tool diameter, because the number of revolutions per minute of the cutter decreases with its increasing diameter.

2.1.4 Number of Cutting Edges and Tool Diameter

The cutting is performed by all the cutting edges while the surface geometry is generated only by the cutting edge with the largest radius. Thus, the tasks are separated, i.e feed per revolution, f is responsible for the surface roughness and feed per tooth f_z for tool wear

The matching tool diameter can be calculated using Eqn. 2.4 and optimum f_z values for minimum tool wear as, [8]

$$d_T = \frac{\frac{d_W^2}{2}[1-\cos(\frac{zf_z}{d_W})]-d_W R_z[1-\cos(\frac{zf_z}{d_W})]-R_z^2}{R_z\cos(\frac{zf_z}{d_W})-\frac{d_W}{2}[1-\cos(\frac{zf_z}{d_W})]} \quad \text{.......................(2.7)}$$

Given the diameters of the workpiece and the tool, the number of cutting edges should be chosen in such a way that the feed per revolution is optimal.

2.1.5 Influence of Cutting Speed

The workpiece is milled along a spiral where the width of contact is equal to the lead a_p. The feed path is equivalent to the length of this path curve, l_f, and is calculated as,

$$l_f = l_{ax}\sqrt{1+(\frac{\pi d_w}{a_p})^2} \quad \text{.........................(2.8)}$$

where,

l_{ax} = length of the workpiece

If economic tool life travels are to be achieved, the cutting speed has to be chosen in a relatively narrow range

2.1.6 Influence of Feed per Tooth on Tool Life Travel

Higher feeds lead to higher mechanical stresses on the cutting edge due to increased chip sections.

2.1.7 Influence of Cutting Process on the Workpiece temperature

High temperature in the transformation zone heats the chips up to their melting temperature. Workpiece and the tool however, remain relatively less heated. Hence, the thermal strain at the boundary layer of the workpiece remains relatively low. The short duration of heating up of the tool and the workpiece during the actual cutting process is followed by a long phase of cooling down and hence,the maximum temperature in case of turn-milling is less than that in case of continuous cutting. Therefore, for turn-milling of very hard materials, higher cutting speeds are allowed to be used in comparison to turning.

2.2 Orthogonal Turn-Milling

Orthogonal turn-milling can be used only for external machining of rotationally similar workpieces [7].

2.2.1 Characteristics of Orthogonal Machining

Use of orthogonal turn-milling for machining results in following advantages:

1. The reduction of cutting forces improves the dimensional and form accuracy, especially
   with thin walled workpieces.
2. Several cutting edges are in contact with the workpiece at all times. This prevents vibrations and reduces tool wear.
3. High surface quality is achieved at extremely large speed ratios and is comparable to that achieved by grinding or honing.

4. The so called ventilation effect of the tool during the non-cutting period and the transfer of heat from the machining zone by the chips keep the workpiece temperature relatively low and therefore prevents workpiece deformations.
5. Because of the intermittent cutting, short chips are formed. So automatic chip disposal is not a problem.
6. Because of low rotation of the workpiece, thin walled workpieces rarely show the drifting or deformations caused by centrifugal forces.

2.2.2 Effect of Eccentricity

Referring to Fig. 2.4, [7]

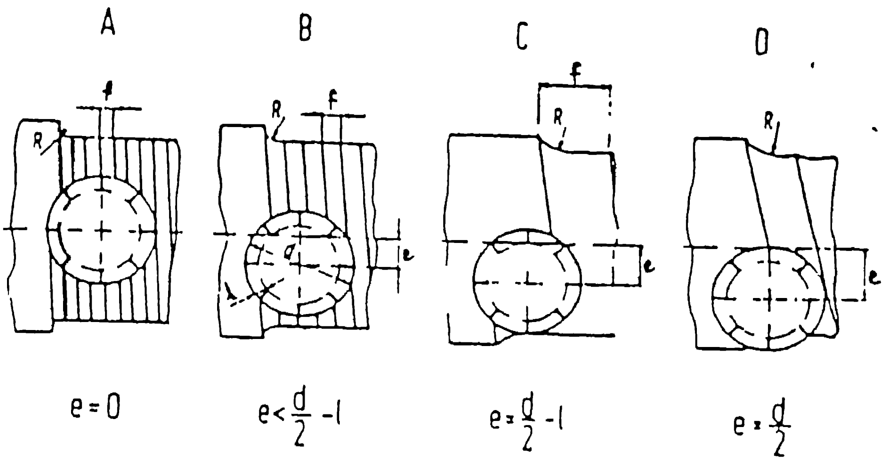


Fig. 2.4 : Possible arrangements of workpiece and tool

a. when the eccentricity $e < d/2 - l$

The maximum feed rate can be increased up to the length of the projection of the minor cutting edge onto the workpiece. nevertheless, a disadvantage of this machining method is the formation of parabolic chamber of shafts which do not correspond to the angle between the major and the minor cutting edge.

b. when, $e = d/2 - l$

In this case, maximum feed rate can be realized, because the length of the contact zone between the axle center of the workpiece and the minor cutting edge reaches its maximum. A cutting process free of vibrations is guaranteed. since there is always more than one cutting edge in contact with the workpiece.

c. when $e = d/2$

This reduces the possible feed rate to a minimum. Below this eccentricity value, there is no possibility to reach the cylindrical surfaces.

2.2.3 Chip Geometry

Chip thicknesses ranging from zero to a maximum are obtained depending upon the feed rate and the tool revolution. The length of the chip depends on the ratio of rotational speed of the cutter to that of the workpiece.

2.2.4 Geometrical accuracy

The main question is how to avoid waviness and non-circularity of machined surfaces during intermittent cuts of the circular jobs.

a. Orthogonal high speed turn-milling may cause a facet formation on the cylindrical surface because of the material left between two cuts using intermittent machining It may be helpful to use high ratio of rotational speed of the cutter to that of the workpiece.

b. Wave formation in the longitudinal direction may be caused. this surface fault looks like thread-like waviness. There are two different patterns of it. The first one is produced if the minor cutting edge is not in contact with the desired radius of the workpiece during its rotation. To minimize this, an angle of zero degrees between the longitudinal axis of the workpiece and the minor cutting edge must be observed. The second pattern arises when the feed rate is higher than the length of the minor cutting edge, projected onto the longitudinal axis of the workpiece.

   Therefore, the right number of cutting edges, the optimal geometry of major and minor cutting edges, the relations of the two cutting speeds, the feed rates and the eccentricity have an influence on the geometrical accuracy

Chapter 3

Experimentation

3.1 Equipment

The present work on ' Orthogonal Turn-Milling ' was carried out using the following equipment.

1. A Vertical Milling Machine,

2. An attachment for workpiece rotation,

3. A surface-finish measurement device (SURTRONIC 10) ,

3.1.1 The Vertical Milling Machine

The machine used for the experimentation is 'H.M.T - FN1PV- Vertical Milling Machine.'

The vertical milling machine was selected because the basic requirement was to have the cutter and the workpiece axes perpendicular to each other. As the milling cutter was held with its axis vertical, the workpiece was held between the centres on the machine-table with its axis horizontal. The attachment for rotating the workpiece was rigidly clamped using T-slots on the machine table. The axial-auto-feed was provided to the workpiece by

moving the machine table axially. The machine permitted to have the axial feed in left and right directions.

The machine had the following speed and feed characteristics :

Cutter speeds available (RPM): 45, 63, 90, 125, 180, 250, 355, 500, 710, 1000, 1400, 2000

Axial auto-feeds available (mm/min.): 8, 9, 10, 11.2, 12.5

3.1.2 The Attachment for Workpiece Rotation

The special attachment for workpiece rotation was required because the machine did not have the provision to rotate the workpiece. For this purpose, a three phase a.c. electrical motor was selected with the following characteristics

Make: REMI

Speed. 25 RPM

Power: 0.3 HP

Electrical supply needed · 415 Volts a.c. , 50 Hz, 3 Phase

The clamping system fabricated for the motor served the following purposes.

i) To maintain the exact vertical distance of the live centre of the workpiece from the machine-table.

ii) To fix the motor rigidly on the machine-table so as to minimize the vibrations.

3.1.3 The Surface-finish Measurement Device

The surface-finish measurement device used was ' SURTRONIC 10 ' which is a battery operated, hand held instrument used to measure surface texture. It provides a numerical assessment of the surface roughness of a surface by the R_a method.

Specifications of the ' SURTRONIC 10 '.

1. Display : LCD type, Units- μm, μin

2. Measuring Range : 0.1 μm to 40 μm

3. Traverse Length : 5 mm

4. Traverse Speed : 2 mm/s

5. Stylus : Diamond, radius = 5 μm

Method of Use:

Before using, the instrument was calibrated against the standard located inside the carrying case of the instrument. The unit-selector switch was positioned for μm unit. The stylus-guard was removed from the stylus and the instrument was placed in an upright position on the surface of the workpiece where the surface-finish was to be measured. As the start button on the top of the instrument was pressed, the stylus traversed a 5 mm length on the workpiece-surface. The resulting measurement in terms of the R_a-value was displayed directly on the LCD screen.

3.2 Selection of Milling-Cutter and the Workpiece

3.2.1 Milling-Cutter

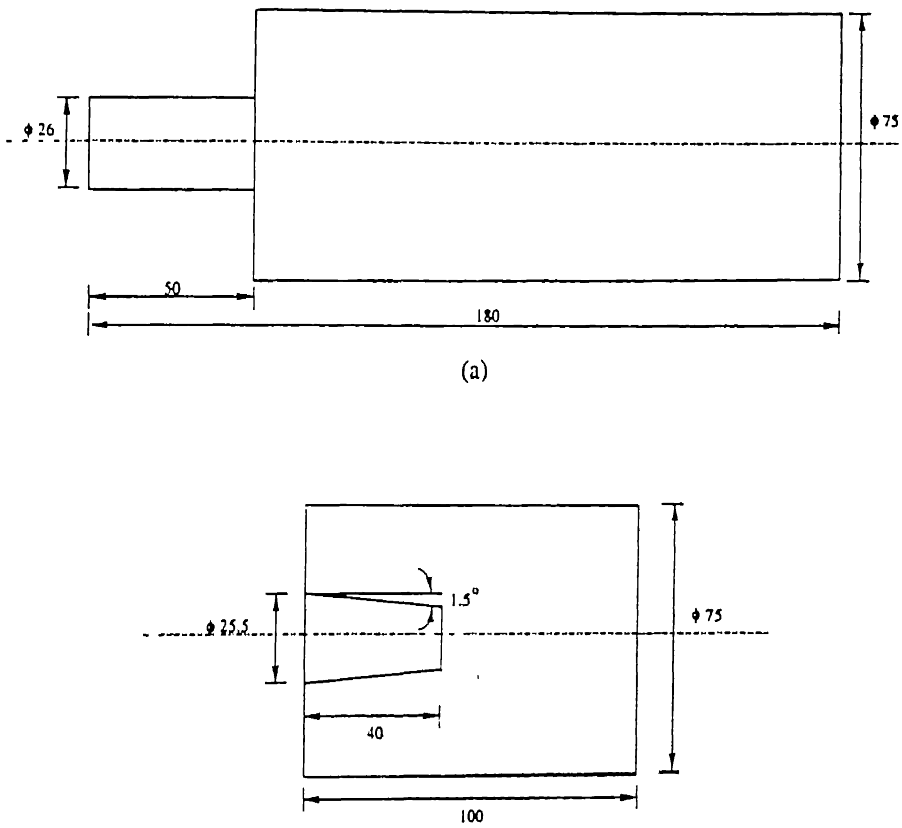
Type	Diameter (mm)	No. of teeth	Primary clearance angle	Positive radial rake angle	Helix Angle	Material
Shank type End-Mill	10	4	7°	8°	15°	HSS

Table 3.1 : Specifications of milling cutter

3.2.2 Workpiece

The workpiece selected for the experimentation is as shown in Fig 3.1. The workpiece dimensions were decided so as to facilitate its clamping and the transmission of

rotary motion by means of a dog-carrier. The workpiece materials selected are brass and Mild-Steel.



(a)

(b)

All dimensions are in mm

(scale 1:2)

Fig 3.1 · Workpieces used for turn-milling

(a) mild steel (b) brass

3.3 Plan of Experiments

The experiments were planned using statistical technique so that the useful results could be obtained by performing minimum number of experiments.

The ' Central Composite Rotatable Design ' for two variables was selected. [9] It is explained in brief as follows :

The general form of a quadratic polynomial is illustrated by the following equation.

$$y_u = b_0 + \sum_{i=1}^{k} b_i x_{iu} + \sum_{i=1}^{k} b_{ii} x^2_{iu} + \sum_{i<j}^{k} b_{ij} x_{iu} x_{ju} \quad \text{.......... ....(3.1)}$$

Here, x_{iu} represents the level of the i^{th} factor in the u^{th} experiment.

where,

k = no. of variables,

x_{iu} , x_{ju} = input variables,

b_0, b_i, b_{ii}, b_{ij} = regression constants,

y_u = output response at the u^{th} observation

The design for two variables is as shown in Table 3.2.

Sr. No	X_0	X_1	X_2	X_1^2	X_2^2	X_1X_2	Y
1	1	-1	-1	1	1	1	Y_1
2	1	1	-1	1	1	-1	Y_2
3	1	-1	1	1	1	-1	Y_3
4	1	1	1	1	1	1	Y_4
5	1	-1 414	0	2	0	0	Y_5
6	1	1.414	0	2	0	0	Y_6
7	1	0	-1 414	0	2	0	Y_7
8	1	0	1.414	0	2	0	Y_8
9	1	0	0	0	0	0	Y_9
10	1	0	0	0	0	0	Y_{10}
11	1	0	0	0	0	0	Y_{11}
12	1	0	0	0	0	0	Y_{12}
13	1	0	0	0	0	0	Y_{13}

Table 3.2 : Central composite rotatable design-for k = 2

Here $X_0 = 1$.

The columns headed X_0, X_1, X_2, X_1^2, X_2^2, X_1X_2 were completed. The two-way array with 6 columns and 13 rows comprised the X-matrix of the x-variables. The corresponding values of the Y were placed to the right column. The actual Y- values for all the 13 experiments are given in Tables 4 1 and 4 2. For each column, the X-value was multiplied by the corresponding Y-value and the sum was calculated over the 13 rows. These sums are denoted by (0y), (1y), (2y) and so on. From these values, the regression coefficients were calculated directly using the equations given below [10].

$$b_0 = 0.2(0y) - 0.1\sum iiy$$
$$\sum iiy = (11y) + (22y)$$
$$b_i = 0.125(iy)$$
$$b_{ii} = 0.125(iiy) + 0.01875\sum(iiy) - 0.1(0y)$$
$$b_{ij} = 0.25(ijy)$$

In the present analysis of the experiments, the effects of two input variables viz. cutter-speed (RPM) and axial feed-rate (mm/min.) have been studied on the surface-finish (R_a value) of the workpiece. A preliminary step was to set up the relations between the coded x-scales and the original scales in which the levels were recorded. In design scale, the lowest and the highest values of x are -1.414 and 1.414 [10].

For the experimentation, the ranges of the cutter-speed and the axial feed-rate were based on the availablemachine capability as:

Cutter speed N_T = 500 - 2000 RPM

Axial feed rate f = 8 - 12.5 mm/min.

x = -1.414 when N_T = 500 RPM , f = 8 mm/min.

x = 1 414 when N_T = 2000 RPM , f = 12.5 mm/min.

In general,

x = a + b .(variable) [10]

a and b were chosen to satisfy the desired conditions at the ends of the scale as explained below.

(1) Cutter-speed (RPM):

$$x = a + b \quad N_T$$

when $x = -1\ 414$, $N_T = 500$ RPM and $-1.414 = a + b \quad 500$

when $x = 1.414$; $N_T = 2000$ RPM and $1.414 = a + b \,.\, 2000$

on solving these two equations simultaneously, we get,

$a = -2\ 356$

$b = 1.885$, hence,

$$x = -2.356 + 1.885 \;.\; N_T \quad \ldots\ldots\ldots\ldots\ldots\ldots(3\ 2)$$

(2) Axial Feed-rate (mm/min.):

$$x = a + b \,.\, f$$

when $x = -1.414$, $f = 8$ mm/min. and $-1.414 = a + b \,.\, f$

when $x = 1.414$, $f = 12.5$ mm/min. and $1.414 = a + b \quad f$

on solving these two equations simultaneously, we get,

$a = -6\ 44$

$b = 0.628$. hence,

$$x = -6.44 + 0.628 \cdot f \quad \text{.......................................} (3.3)$$

From Eqns. 3.2 and 3.3, cutter speeds and axial feed rates corresponding to levels x = -1, 0, 1 were determined. The complete conversion is tabulated in Table 3.3.

X	Cutter speed N_T (RPM)	Axial feed rate f (mm/min)
-1.414	500	8
-1	719	8.66
0	1249	10.25
1	1780	11.85
1.414	2000	12.5

Table 3.3 : Conversion table

Since the exact intermediate cutter speeds and axial feed rates were not available, the experiments were conducted for their nearest available values as given in Tables 4.1 and 4.2.

The experiments were conducted according to the 'plan of experiments' as per sequence given in Table 3.4.

Expt. No.	Sr.No. as per design of expts. (Table 3.1)	Cutter speed N_T (RPM)	Axial feed rate f (mm/min)
1	7	1000	8
2	2	1400	9
3	1	710	9
4	5	500	10
5	6	2000	10
6	9	1000	10
7	10	1000	10
8	11	1000	10
9	12	1000	10
10	13	1000	10
11	3	710	11.2
12	4	1400	11.2
13	8	1000	12.5

Table 3.4 · Plan of experiments

3.4 Experimental Procedure

The aim of the experiments was to evaluate the surface finish of the machined surface of the workpieces machined by orthogonal turn-milling and to compare it with that in case of turning carried out under comparable cutting conditions.

i) Constant Parameters ·

(a) Rotary Speed of the Workpiece = 25 RPM

(b) Depth of Cut = 0.3 mm

ii) Variable Parameters (as given in Tables 4.1 and 4.2):

(a) Rotary Speed of the Cutter (RPM): 500, 710, 1400, 2000

(b) Axial Feed-rate of the Workpiece (mm/min.): 8, 9, 10, 11.2, 12.5

The experimental set-up is schematically shown in Fig. 3.2. and the photograph of the experimental set-up is shown on page no. 28

The experiments were conducted as per plan of experiments described in section 3 3. For each experiment, the cutting parameters were first set as given in Tables 4 1 and 4 2. The machine was then started and the workpiece was machined by turn-milling. The surface-finish of the workpiece was measured in terms of the R_a- value after each experiment using the surface-finish measuring device (SURTRONIC 10) as described in subsection 3.1 3.

3.5 Experiments on Turning

To test the feasibility of the turn-milling process in comparison to turning and to compare the effect of various cutting parameters on the surface finish in both of these processes, the experiments were conducted on a turning lathe. The brass and mild-steel workpieces identical to those machined by turn-milling were machined by turning under comparable cutting conditions. The surface finish achieved by turn-milling and turning were then compared.

i) Constant parameter

Depth of cut = 0.3mm

ii) Variable parameters

(a) Speed of the workpiece: Since turning could not be carried out at the same speeds as in case of turn-milling, due to the restriction in available machine capability, lower range of speeds was selected, one speed being common in both the processes.

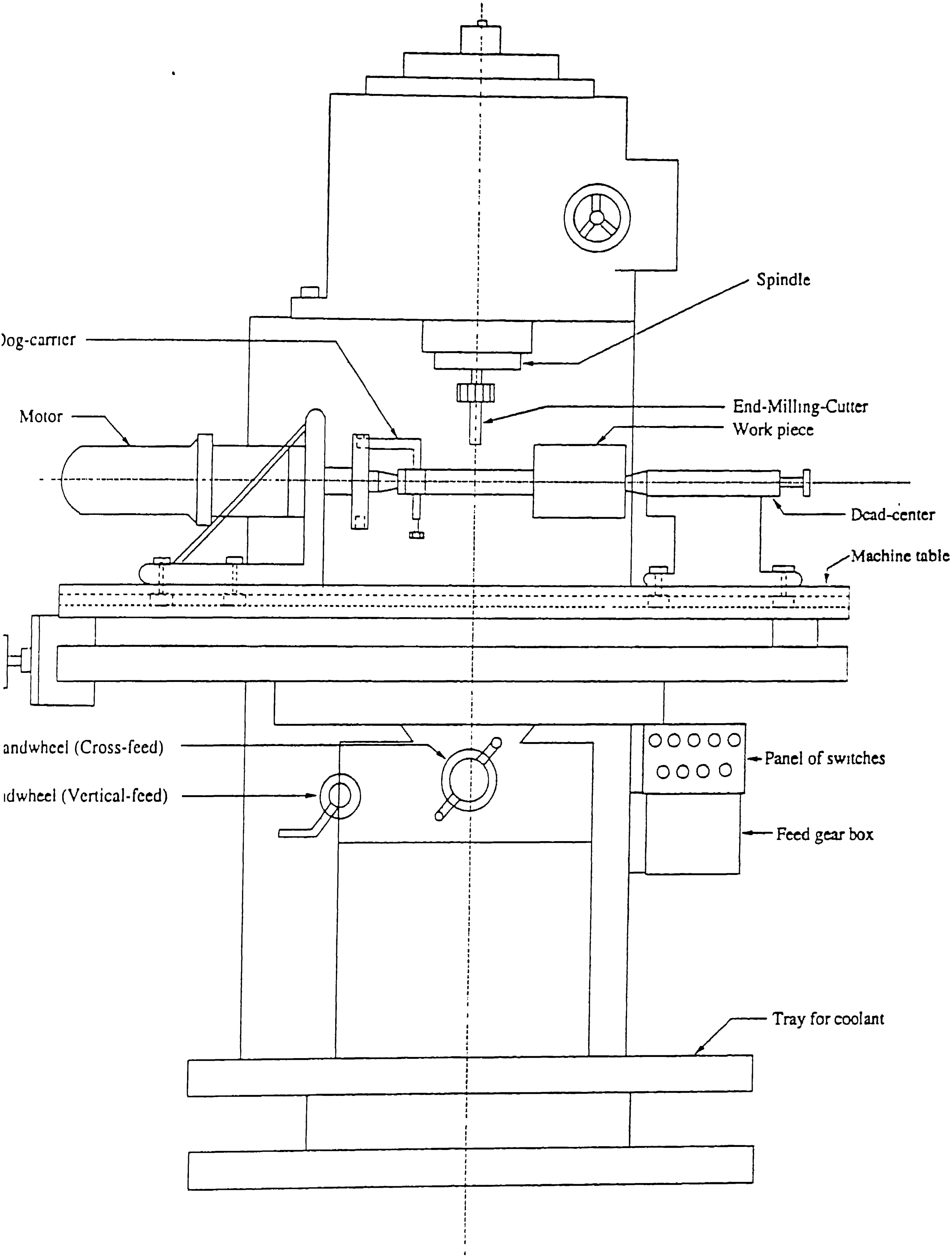
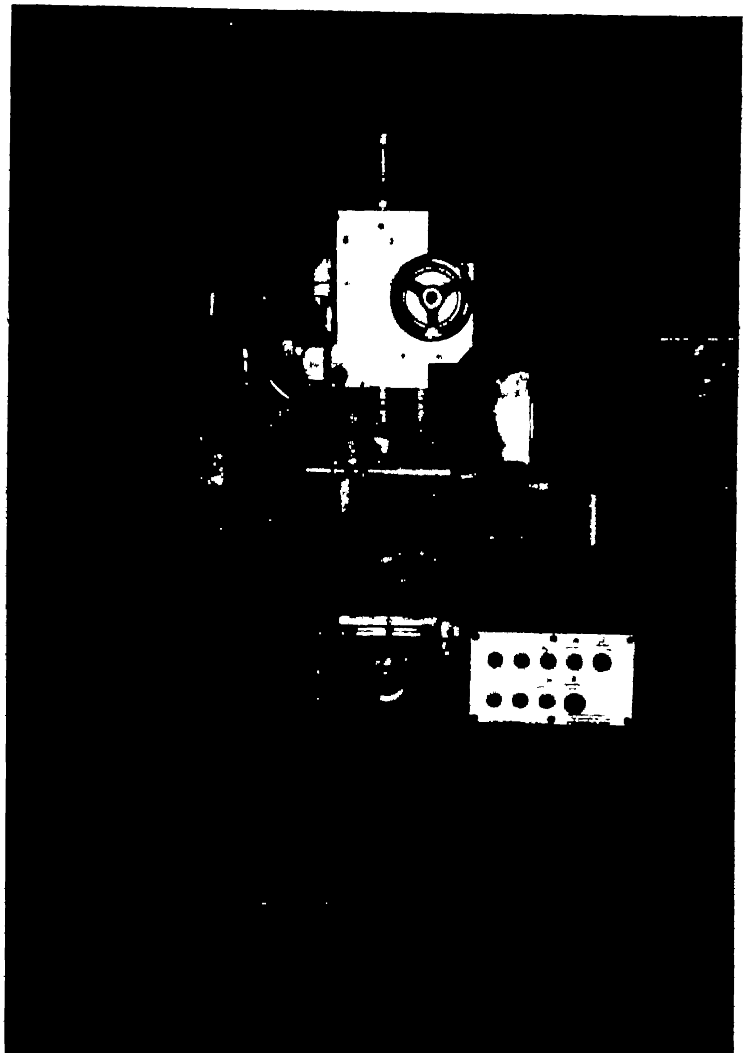


Fig. 3.2 Experimental set-up for Orthogonal Turn-milling.



A photograph showing the Experimental set-up for Orthogonal Turn-Milling

Speeds of the workpiece (RPM): 250, 320, 400, 500

(b) Axial feed rate: since in the lathe machine, feeds are in mm/rev., the equivalent feed in mm/rev. in case of turn-milling was calculated.

$$f_e = \frac{f}{N_w} \pm \frac{f}{N_T Z} \qquad \text{(3.4)}$$

where,

f_e = equivalent feed (mm/rev.),

f = table feed (mm/min.),

N_w = rotational speed of the workpiece (RPM),

N_T = rotational speed of the milling cutter (RPM),

Z = no of teeth on the milling cutter

In the experiments on turn-milling, Z = 4.

Range of cutter speeds N_T: 500-2000 RPM

Speed of the workpiece N_w = 25 RPM

Hence, for any value of N_T in the specified range,

$$\frac{f}{N_W} >> \frac{f}{N_T Z}$$

Hence

$$f_e \cong \frac{f}{N_W}$$

Table 3.5 shows the actual table feeds used in turn-milling and corresponding equivalent feeds

f (mm/min.)	f_e (mm/rev.)
8	0.32
9	0 36
10	0.40
11.2	0.448
12.5	0.50

Table 3.5 · Actual table feeds and equivalent feeds in turn-milling

Hence, in the experiments on turning, the following values of feeds were used.

feed (mm/rev):0.3, 0.35, 0.40, 0.45

The experiments were conducted for all the combinations of workpiece speeds and feeds for both the workpiece materials. After each experiment, surface finish of the machined surface was measured as described in subsection 3 1.3. Machining parameters as the input variables and the surface finish as the output response are depicted in tables 4.3 and 4.4.

The surface finish achieved in turning was then compared to that achieved in case of turn-milling for both the workpiece materials. The chip geometry of the chips produced in turning and orthogonal turn-milling were also compared.

Chapter 4

Results and Discussion

In this chapter, the effects of cutter speed and axial feed rate on the surface finish of the machined workpiece in case of turning and orthogonal turn-milling are discussed.

The discussion is based on the experimental observations given in Tables 4 1, 4.2, 4.3 and 4 4 The analysis has been carried out for orthogonal turn-milling of brass and mild steel workpieces. The results of turn-milling and turning processes have been compared for both the workpiece materials

4.1 Orthogonal Turn-milling of Brass Workpiece

Constant machining conditions used in orthogonal turn-milling of brass workpiece

(a) Rotational speed of the workpiece = 25 RPM

(b) Depth of cut = 0.3 mm

From the experimental results given in Table 4 1, the constants in the Eqn 3.1 are evaluated as per the procedure described in 3.3.

The following response surface equation is obtained for evaluating the surface roughness, y_{sf} (R_a value) in terms of the variables x_1 (cutter speed) and x_2 (axial feed rate). Here, x_1 and x_2 are used as coded level values which can be calculated from Eqns. 3.2 and 3 3.

$$y_{sf} = 1.692 - 0.278x_1 + 0.369x_2 + 0\,07x_1^2 - 0\,007x_2^2 - 0\,099x_1x_2 \quad (4.1)$$

Using Eqn. 4.1, parametric analysis has been carried out as discussed below.

Expt. No.	Cutter speed N_T (RPM)	Axial feed rate, f (mm/min)	Measured Surface Roughness R_a-value (μm)
1	1000	8	1.4
2 .	1400	9	1.3
3	710	9	1.5
4	500	10	2.4
5	2000	10	1 2
6	1000	10	1.6
7	1000	10	1.7
8	1000	10	1.6
9	1000	10	1.6
10	1000	10	1.7
11	710	11.2	2.3
12	1400	11.2	2.0
13	1000	12.5	2.2

Table 4 1. Experimental Results of Orthogonal Turn-milling (Brass-Workpiece.)

4.1.1 Effect of Cutter Speed on Surface Roughness

Using Eqn.4.1, Surface roughness, y_{sf}, is calculated for ten random values of x_1 (cutter speed) within its range and for three different constant values of x_2 (axial feed rate).

Figure 4 1 shows the variation of surface roughness, R_a with the cutter speed, N_T at three constant levels of axial feed rate, f.

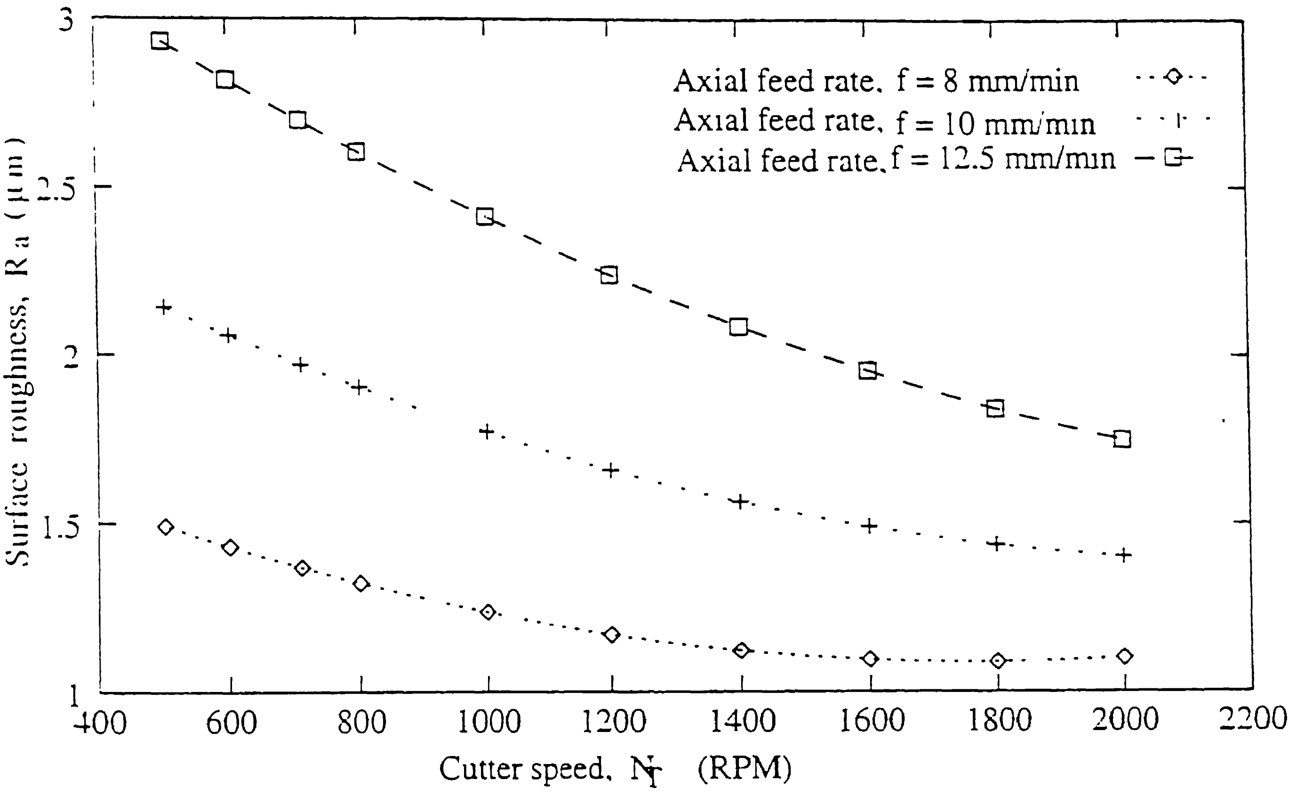


Fig. 4.1 : Effect of cutter speed on surface roughness in orthogonal turn-milling (brass workpiece)

It is observed that the surface roughness, R_a decreases with increase in cutter speed, N_T Hence, surface finish of the machined workpiece improves with increase in cutter speed Furthermore, the surface roughness is found to increase with increase in axial feed rate, f. The continuously falling trend of the curves indicates that the surface finish of the machined surface is expected to improve further with the cutter speeds exceeding 2000 RPM.

Hence, it is better to use the cutter speeds as high as possible to improve the surface finish of the machined workpiece.

4.1.2 Effect of Axial Feed Rate on Surface Roughness

Using Eqn. 4 1, y_{sf} (surface roughness) is calculated for ten random values of x_2 (axial feed rate) within its range and for three different constant values of of x_1 (cutter speed)

Figure 4.2 shows the variation of surface roughness, R_a with the axial feed rate, f at three constant levels of cutter speed, N_T

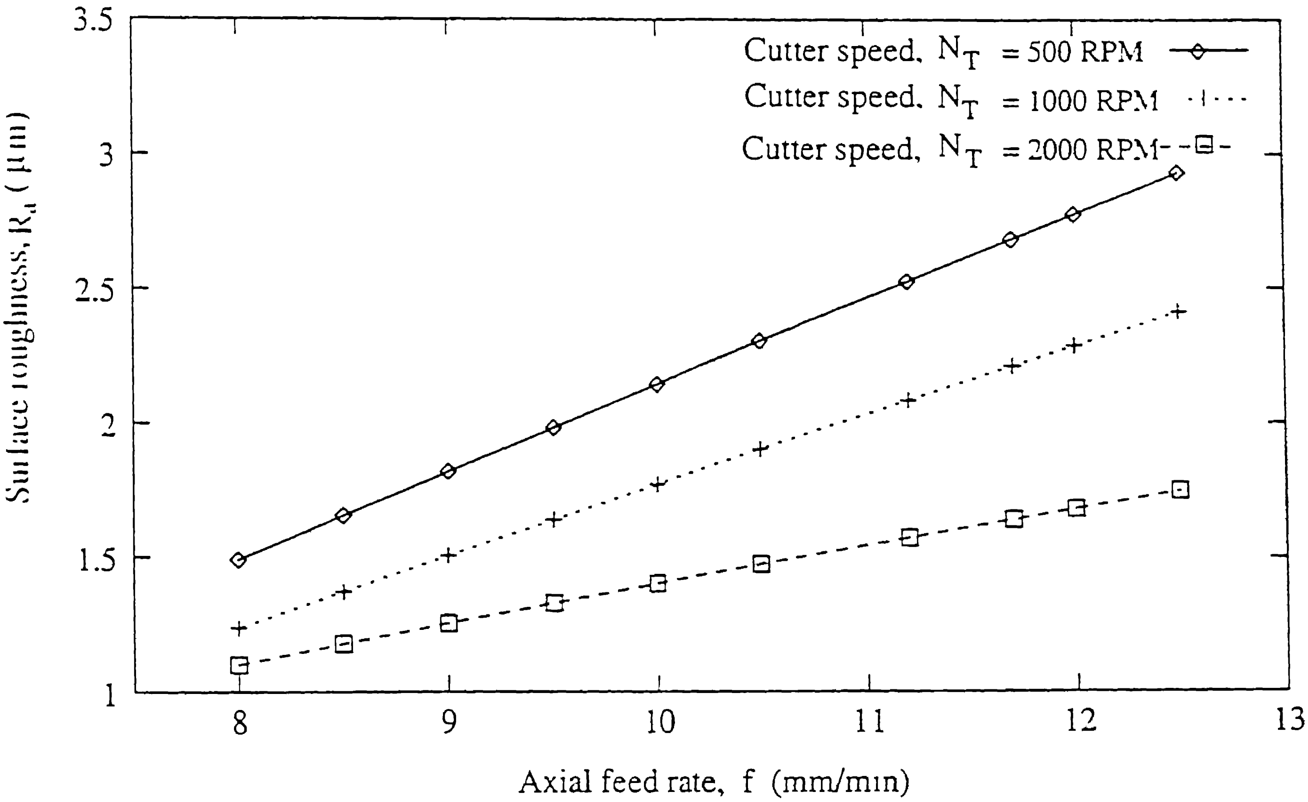


Fig. 4.2 : Effect of axial feed rate on surface roughness in orthogonal turn-milling (brass workpiece)

It is observed that the surface roughness, R_a increases with increase in axial feed rate, f. Hence, surface finish of the machined workpiece deteriorates with increase in axial feed rate. Furthermore, the surface roughness is found to decrease with increase in cutter speed, N_T. The continuously falling trend of the curves with decreasing feed rates

indicates that the surface finish of the machined surface is expected to improve further with the lower values of axial feed rate.

Hence, it is better to use the lower values of axial feed rate to improve the surface finish of the machined workpiece

4.2 Orthogonal Turn-Milling of Mild-Steel Workpiece

Constant machining conditions used in orthogonal turn-milling of mild-steel workpiece

(a) Rotational speed of the workpiece = 25 RPM

(b) Depth of cut = 0.3 mm

From the experimental results given in table 4.2, the constants in the Eqn. 3.1 are evaluated as per the procedure described in 3.3.

The following response surface equation is obtained for evaluating the surface roughness, y_{sf}, (R_a value) in terms of the variables x_1 (cutter speed) and x_2 (axial feed rate). Here, x_1 and x_2 are used as coded level values which can be calculated from Eqns.3.2 and 3.3.

$$y_{sf} = 2.343 - 0.204x_1 + 0.699x_2 - 0.01x_1^2 + 0.415x_2^2 - 0.069x_1x_2 \qquad (4.2)$$

Using Eqn.4 2, parametric analysis has been carried out as discussed below.

Expt. No.	Cutter speed N_T (RPM)	Axial feed rate, f (mm/min)	Measured Surface Roughness R_a-value (μ m.)
1	1000	8	2.4
2	1400	9	2.0
3	710	9	2.4
4	500	10	2.6
5	2000	10	1.9
6	1000	10	2.2
7	1000	10	2.3
8	1000	10	2.3
9	1000	10	2.2
10	1000	10	2.3
11	710	11.2	3.5
12	1400	11.2	3.3
13	1000	12.5	4.3

Table 4.2: Experimental Results of Orthogonal Turn-milling (Mild-steel Workpiece.)

4.2.1 Effect of Cutter Speed on Surface Roughness

Using Eqn. 4 2, Surface roughness, y_{sf}, is calculated for ten random values of x_1 (cutter speed) within its range and for three different constant values of x_2 (axial feed rate)

Figure 4 3 shows the variation of surface roughness, R_a with the cutter speed at three constant levels of axial feed rate, f.

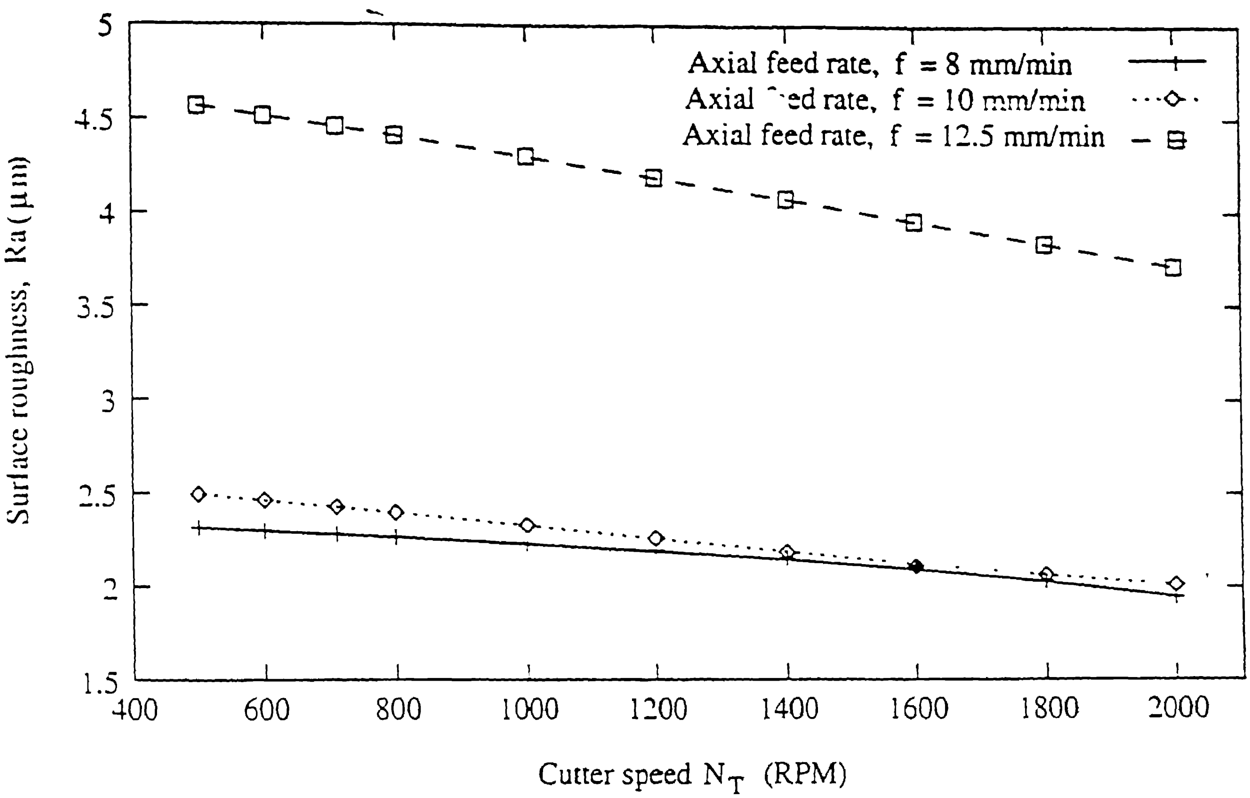


Fig. 4.3 : Effect of cutter speed on surface roughness in orthogonal turn-milling (mild steel workpiece)

Similar results are obtained as in case of brass, i.e., the surface roughness, R_a decreases with increase in cutter speed, N_T. Hence, surface finish of the machined workpiece improves with increase in cutter speed. Furthermore, the surface roughness is found to increase with increase in axial feed rate, f. The roughness of the machined surface of the mild-steel workpiece is found to be higher than that of the brass workpiece for comparable combinations of cutter speed and axial feed rate. The continuously falling trend of the curves indicates that the surface finish of the machined surface is expected to improve further with the cutter speeds exceeding 2000 RPM.

4.2.2 Effect of Axial Feed Rate on Surface Roughness

Using Eqn. 4.2, y_{sf} (surface roughness) is calculated for ten random values of x_2 (axial feed rate) within its range and for three different constant values of x_1 (cutter speed).

Figure 4.4 shows the variation of surface roughness, R_a with the axial feed rate, f at three constant levels of cutter speed, N_T.

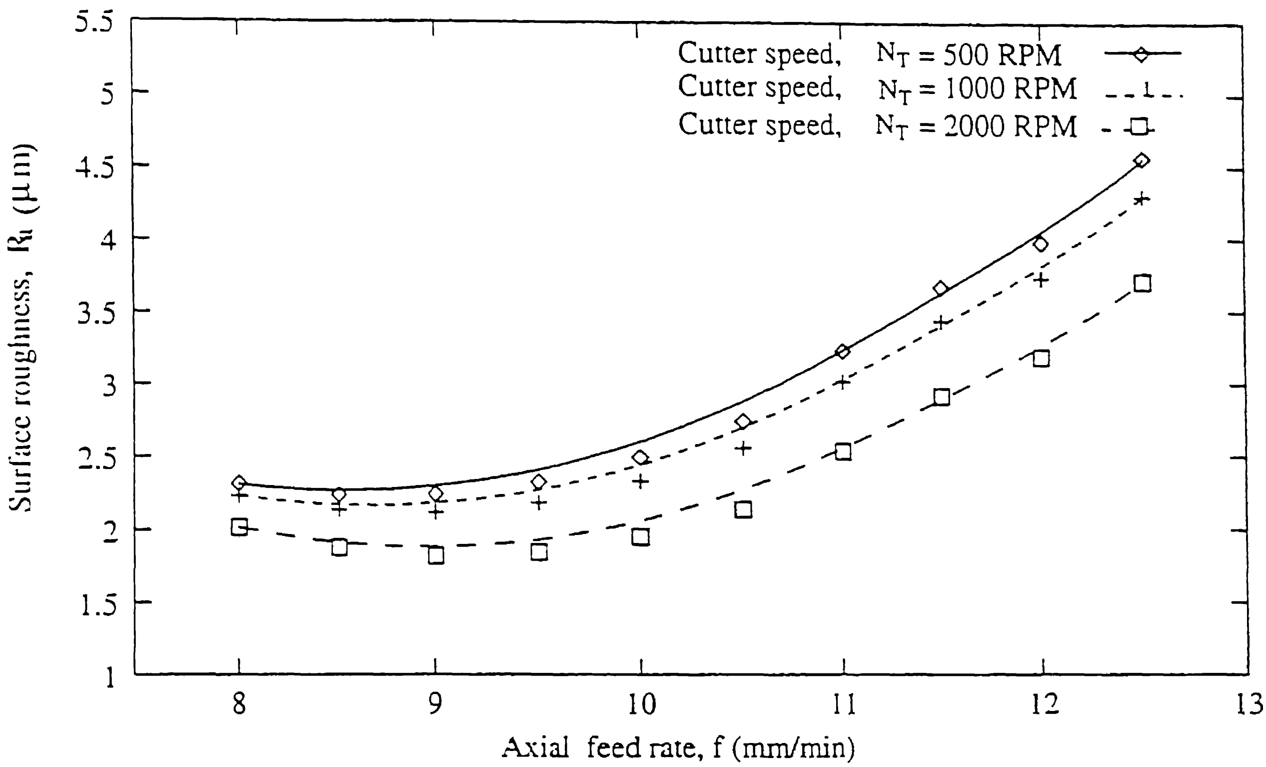


Fig. 4.4 : Effect of axial feed rate on surface roughness in orthogonal turn-milling (mild steel workpiece)

Similar results are obtained as in case of brass, i.e. the surface roughness, R_a increases with increase in axial feed rate, f. Hence, surface finish of the machined workpiece deteriorates with increase in axial feed rate. Furthermore, the surface roughness is found to decrease with increase in cutter speed, N_T. The roughness of the machined surface of the mild-steel workpiece is found to be higher than that of the brass workpiece for comparable combinations of cutter speed and axial feed rate. The continuously falling trend of the curves with decreasing feed rates indicates that the surface finish of the machined surface is expected to improve further with the lower values of axial feed rate.

4.3 Comparison of Orthogonal Turn-Milling and Turning of Brass Workpiece

4.3.1. Effect of Workpiece Speed on Surface Roughness

The experimental results of turning of brass workpiece are given in Table 4.3.

Expt No	Workpiece speed N_W (RPM)	Axial feed rate f (mm/rev.)	Measured Surface Roughness R_a-value (μm)
1	250	0.30	22.6
2	320	0 30	21.7
3	400	0.30	21.5
4	500	0.30	18.6
5	500	0 35	21.6
6	400	0 35	22.5
7	320	0.35	23.5
8	250	0.35	24.5
9	250	0.40	27.4
10	320	0.40	26.0
11	400	0 40	25.3
12	500	0.40	23.6
13	500	0.45	29 8
14	400	0.45	30.7
15	320	0.45	31.3
16	250	0.45	31.7

Table 4.3· Experimental results of Turning (Brass-workpiece)

Figure 4.5 shows the variation of surface roughess, R_a with the workpiece speed, N_w at three constant levels of axial feed rate, f. By comparing the curves in Fig. 4.1 and those in Fig 4.5, it is observed that the surface finish achieved by turn-milling is higher than that achieved by turning For the speed of 500 RPM and the feed rates of 8 mm/min (i.e. 0.3 mm/rev) and 10 mm/min (i.e. 0.4 mm/rev) , experiments were conducted both for turn-milling as well as turning

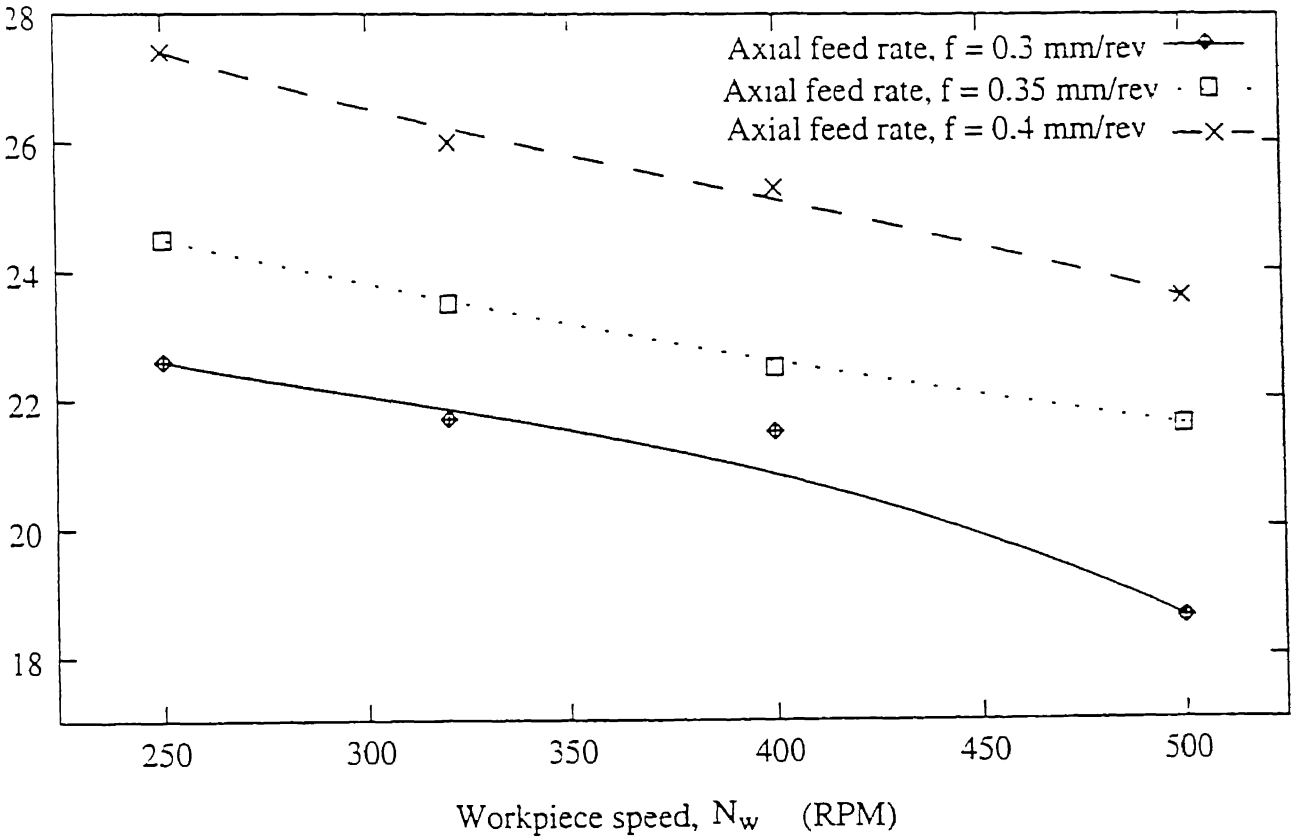


Fig. 4.5 : Effect of workpiece speed on surface roughness in turning (brass workpiece)

For these combinations of speed and feed, the surface roughness, R_a value achieved by turning is found to be about 10 times that achieved by turn-milling. It is expected that for any combination of speed and feed, the surface finish achieved by turn-milling will be higher than that achieved by turning.

4.3.2 Effect of Axial feed rate on Surface Roughness

Figure 4 6 shows the variation of surface roughness, R_a with the axial feed rate, f at three constant levels of workpiece speed, N_w. By comparing the curves in Fig. 4 2 and those in Fig. 4.6, it is observed that the surface finish achieved by turn-milling is higher than that achieved by turning. As explained in 4.3.1, the surface roughness, R_a value achieved by turning is found to be 10 times that achieved by turn-milling

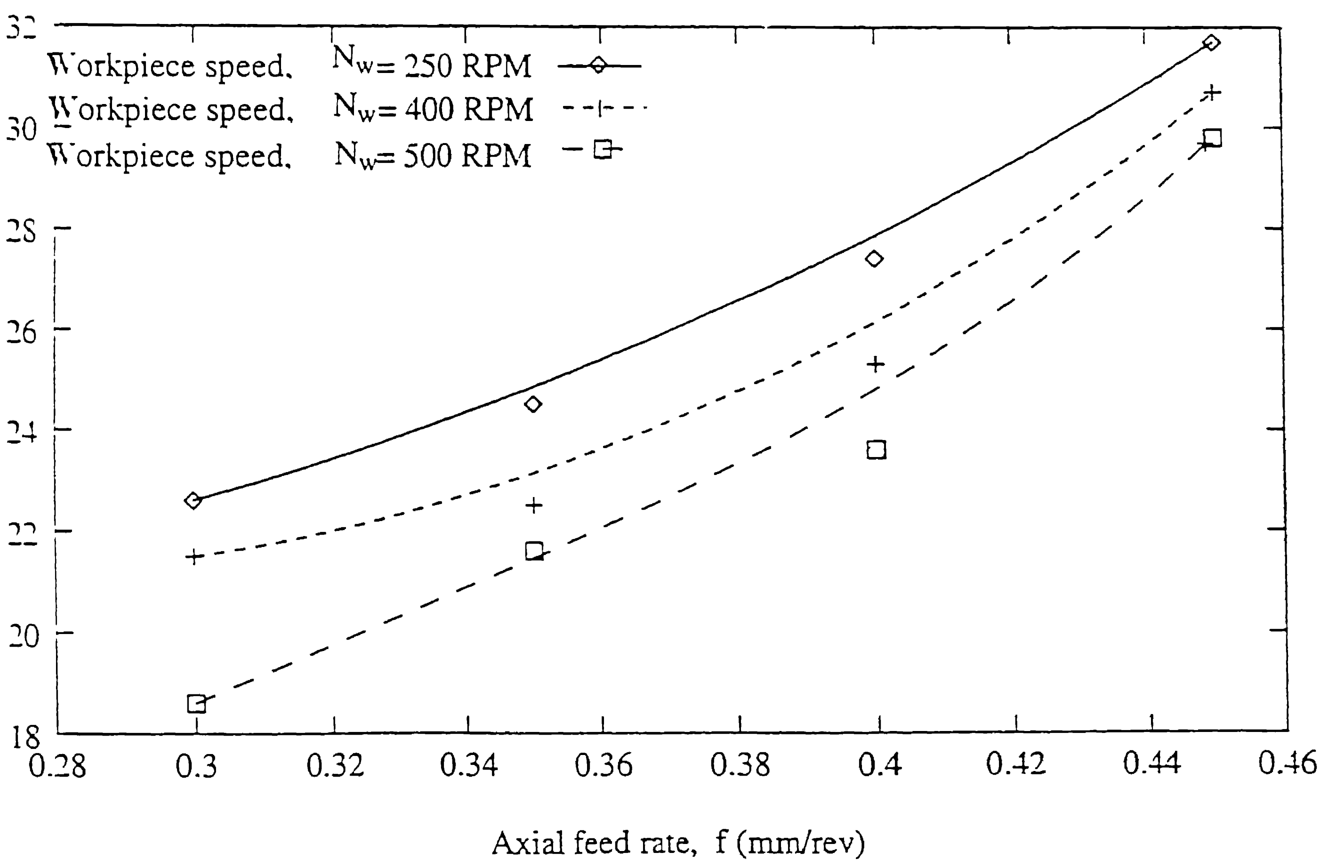


Fig. 4.6 : Effect of axial feed rate on surface roughness in turning (brass workpiece)

4.4 Comparison of Orthogonal Turn-Milling and Turning of Mild Steel Workpiece

4.4.1. Effect of Workpiece Speed on Surface Roughness

The experimental results of Turning of mild steel workpiece are given in Table 4.4.

Expt. No.	Workpiece speed N_W (RPM)	Axial feed rate f (mm/rev.)	Measured Surface Roughness R_a-value (μm.)
1	250	0.30	24.3
2	320	0.30	23.4
3	400	0.30	22.6
4	500	0.30	21.3
5	500	0 35	23 4
6	400	0.35	25.4
7	320	0.35	26.1
8	250	0.35	26.3
9	250	0 40	30.6
10	320	0.40	30.4
11	400	0 40	29.9
12	500	0 40	29.2
13	500	0.45	32.7
14	400	0.45	33.0
15	320	0.45	34.6
16	250	0.45	37.1

Table 4.4: Experimental Results of Turning (Mild steel Workpiece.)

Figure 4.7 shows the variation of surface roughess, R_a with the workpiece speed, N_w at three constant levels of axial feed rate, f. By comparing the curves in Fig. 4.3 and those in Fig. 4 7, it is observed that the surface finish achieved by turn-milling is higher than that achieved by turning For the speed of 500 RPM and the feed rates of 8 mm/min (i e 0 3 mm/rev) and 10 mm/min (i e. 0.4 mm/rev) , experiments were conducted for turn-milling as well as turning For these combinations of speed and feed, the surface roughness, R_a value achieved by turning is found to be about 10 times that achieved by turn-milling.

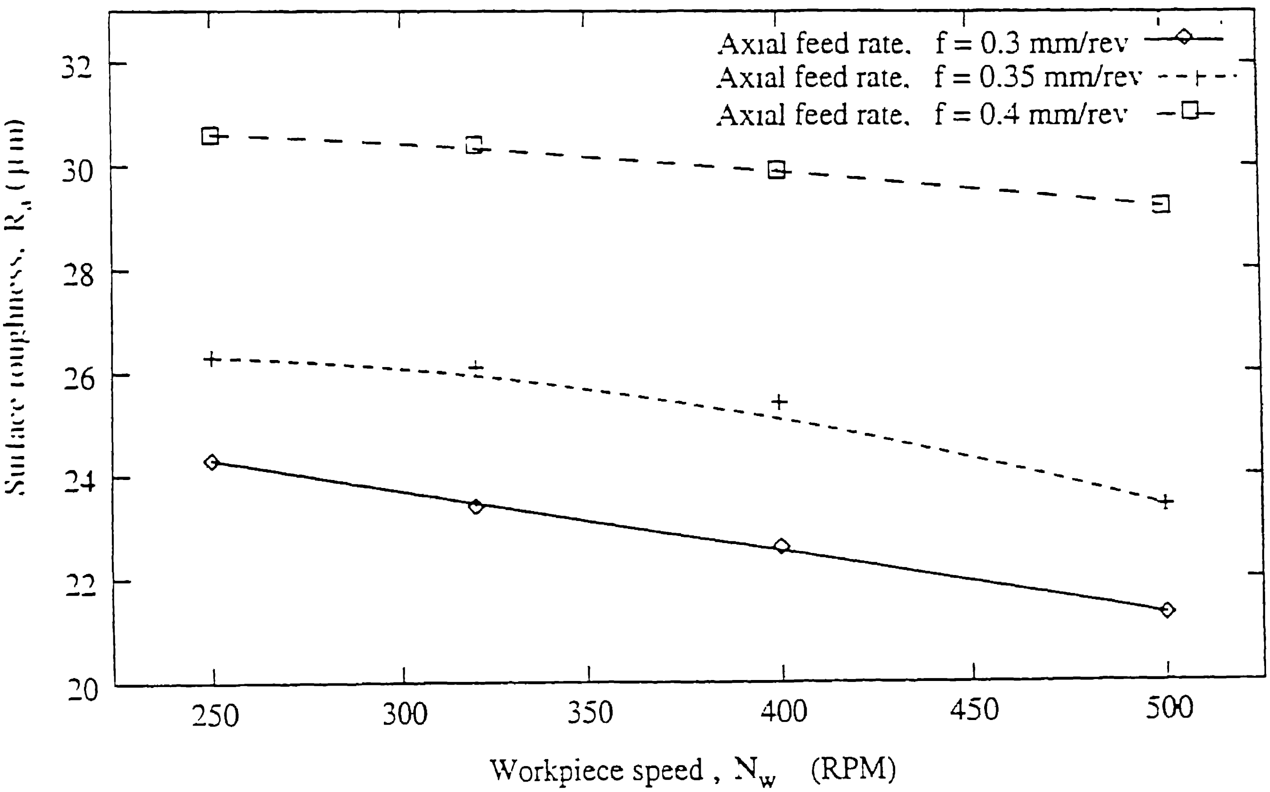


Fig. 4.7 : Effect of workpiece speed on surface roughnness in turning (mild steel workpiece)

4.4.2 Effect of Axial feed rate on Surface Roughness

Figure 4.8 shows the variation of surface roughness, R_a with the axial feed rate, f at three constant values of workpiece speeds, N_w. By comparing the curves in Fig.

4.4 and those in Fig. 4.8, it is observed that the surface finish achieved by turn-milling is higher than that achieved by turning. As explained in 4.4.1, the surface roughness R_a value achieved by turning is found to be 10 times that achieved by turn-milling.

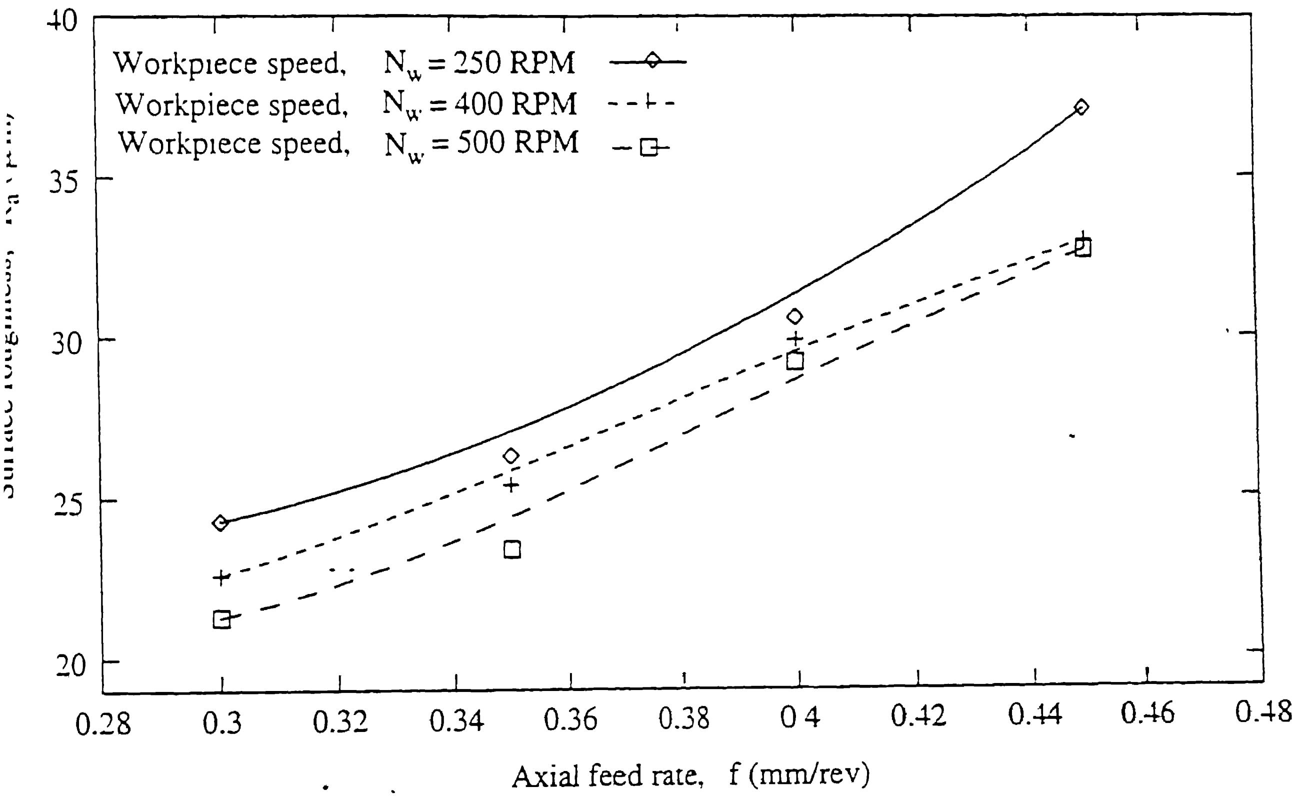


fig. 4.8 : Effect of axial feed rate on surface roughness in turning (mild steel workpiece)

4.5 Comparison of the chips produced in Orthogonal Turn- Milling and Turning.

Very small chips were produced in the experiments of orthogonal turn-milling as compared to the relatively longer chips produced in the experiments of turning in case of mild-steel workpiece. The chip length obtained in turning is found to be approximately six times that obtained in orthogonal turn-milling. Hence, disposal of chips is very easy in orthogonal turn-milling, whereas chip disposal is a problem in turning for the mild steel workpiece.

However, the difference in chip lengths obtained in turning and orthogonal turn-milling of brass workpiece is found to be negligible because brass is more brittle than mild-steel.

Chapter 5

Conclusions and Scope for Future Work

5.1 Conclusions

1. In case of orthogonal turn-milling, the surface finish of the machined surface improves with increase in rotational speed of the cutter and deteriorates with increase in axial feed rate. Hence, orthogonal turn-milling should be carried out at high cutter speeds and low axial feed rates to achieve high surface finish of the machined surface.

2. Even by utilizing relatively low speeds comparable to those used in turning, a very high surface finish of machined surface can be achieved by orthogonal turn-milling for the machining of rotationally symmetrical workpieces. In case of orthogonal turn-milling, Ra value of the surface roughness achieved is about 10 times lower than that achieved in case of turning.

3 In case of orthogonal turn-milling, very small chips are produced contrary to the relatively longer chips produced in case of turning of mild steel. Hence, chip disposal is not a problem when relatively ductile materials like mild steel are machined by orthogonal turn-milling However, the difference in chip lengths obtained in orthogonal turn-milling and in turning is negligible in case of relatively brittle materials like brass.

4 Orthogonal turn-milling can be an alternative to turning for the machining of large and heavy workpieces where relatively low rotational speeds of the workpieces have to be used.

5.2 Scope for Future Work

1. In case of orthogonal turn-milling, measurement of cutting forces needs to be carried out utilizing a dynamometer This will be helpful in understanding the mechanics of the process.

2. The process of orthogonal turn-milling should be analyzed for the measurement of material removal rate as well as tool wear

3 Co-axial turn-milling process is still an open field for research. Co-axial turn-milling can be studied for various parameters such as surface finish, cutting forces and tool wear.

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